

WHAT WE DON'T KNOW ABOUT QUARTZ CLOCKS IN SPACE

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Abstract

An essential element of any space vehicle is the onboard clock. The proper operation of the entire payload is dependent on the performance of the onboard clock or master oscillator. However, there is a noticeable absence of crucial data in the space community regarding space environmental effects as well as circuitry contributions on the performance of quartz clocks. For example, the authors, in a previous paper [1], presented empirical data on dormant quartz oscillators (redundant/stand-by units that are activated in the event of an anomaly in the primary oscillator) to determine the long-term aging performance of oscillators in the non-operating mode. The aging rate data are extremely important for predicting the expected performance of these backup oscillators after 10 or 15 years in space. This paper is an extension of this previous publication, in which other phenomena that may affect the performance of clocks in space are addressed. Issues such as acceleration, spacecraft charging, discharges from floating metal, solar flares, single event upsets, operating temperature, magnetic fields, space debris, and meteorite impacts are addressed. Typically, the theoretical response of quartz clocks to stimuli such as these is fairly well understood; however, the magnitudes of the stimuli on particular spacecraft platforms are not. Analyses suggest that quartz clock performance in space may or may not be significantly degraded due to these phenomena, depending on their magnitudes. This paper is intended to explore ideas and stimulate thought in the space community with the goal of launching more robust clocks in the future.

I. BACKGROUND

In 1880, Jacques and Pierre Curie discovered the piezoelectric properties of quartz. During World War I quartz resonators were used in sonar, and in the 1920s quartz oscillators were first used as stable frequency references to control the frequency of radio broadcasting stations. During World War II, the need for accurate frequency control of military radios caused significant growth for the quartz oscillators industry. In the late 1950s, the first precision quartz clocks were utilized for space applications in the Vanguard Program that successfully placed three satellites into orbit in 11 attempts.

The emergence of applications such as high data rate communication, navigation, and positioning systems, especially those that utilize the Doppler Effect, has increased the demand for better frequency stability in quartz oscillators. Consequently, the performance of quartz oscillators has significantly improved, and they have become the fundamental element in spacecraft for generation of precise

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frequency and time. In addition, precision quartz oscillators have evolved into key building blocks for extremely precise timekeeping instruments such as cesium and rubidium fountains, cesium and rubidium atomic frequency standards, passive hydrogen masers, and others. Since the Vanguard rockets, the majority of spacecraft continue to employ stable quartz-based oscillators as the onboard master clock, referred to as Ultra-Stable Oscillators (USOs), and the proper functioning of the entire payload is often dependent on the performance of these crucial assemblies.

The first USOs for deep space applications were flown onboard the space probes Voyagers 1 and 2. Voyager 2 was launched before Voyager 1 on 20 August 1977 and Voyager 1 was launched 5 September 1977. Voyager 1 remains operational and is on its way to the boundaries of the solar system while the Voyager 2 mission has been terminated. At that time, the Voyager Radio Science team worked closely with Frequency Electronics Inc. to procure five flight-qualified quartz ultra-stable oscillators. These oscillators were designed with dual-ovens and AT-cut crystals, and exhibited a typical Allan deviation of 1×10^{-12} for an integrated time of $\tau = 100$ seconds [2]. From the 1970s, USO design enhancements have been implemented, including the usage of SC-cut crystal and titanium alloy Dewar flasks, that have resulted in significant improvements to the performance of the USOs. For example, present-day space USOs are available with short-term stabilities of 1 to $2 \times 10^{-13}/10$ sec, and with a long-term stability of better than $2 \times 10^{-8}/15$ years. In parallel to the USO improvement efforts conducted by Frequency Electronics Inc, the space community has made significant strides in understanding the space environmental influence on spacecraft, but there is a noticeable absence of crucial data in the community regarding space environmental effects on the performance of quartz-based clocks. Some phenomena that affect the performance of quartz-based clocks in space include acceleration, spacecraft charging and resulting internal discharges, radiation caused by solar flares and other cosmic energies, operating temperature, and magnetic fields. The continuous demand for increased precision required of quartz clocks necessitates a better understanding of the aforementioned phenomena and the resulting effects on the performance of critical parameters such as short- and long-term frequency stability, phase noise, spectral purity (i.e., spurs), and frequency jumps. This paper is intended to explore ideas and stimulate thought in the space community with the goal of launching more robust and more precise quartz clocks in the future.

II. EFFECTS OF ACCELERATION

Dynamic environments common to spacecraft degrade the performance of quartz crystal oscillators. To generate the precise frequencies and time signals crucial to system performance, quartz crystal oscillators are commonly utilized. However, quartz crystal oscillators exhibit degraded performance when subject to accelerating forces, i.e. sine and/or random vibrations. Although the spacecraft environment has traditionally been considered “vibration-free,” it is increasingly clear that low level accelerations and vibrations due to reaction wheels, thrusters, etc. degrade quartz oscillator output enough to impact, in many cases, system level performance.

For the past 40+ years, it has been generally assumed that no on-orbit vibrations of consequence occurred that could affect the onboard communication systems and various other sensors. Obtaining reliable measurements from satellites that would reveal vibration-induced distortions is very difficult and the magnitude of the problem has been to a large extent ignored. The major focus has been on the launch random vibration environment. However, in recent years FEI in concert with various satellite manufacturers has recognized that the onboard environment is dynamic with the presence of micro vibrations caused by thrusters, momentum wheels, and other moving systems. These micro vibrations generate low level spurious outputs and noise within commercial and military communications bands and actually do degrade system performance. For example, the performance of broadband, high data rate communication systems are significantly affected, since low-noise frequency sources play a major role in

achieving a high data rate. Platform dynamics can degrade the signal, which in turn increases the BER (bit error rate), potentially forcing the system to decrease its data rate to maintain a required BER. Communication links between satellites may degrade or completely fail if the low-noise frequency oscillator is affected by the vibration environment. The effects of micro vibration on communication links have been studied on test satellites by ESA and others [3].

Any phase noise degradation in the master oscillator is magnified in higher frequency sources that are directly or indirectly synthesized from the master oscillator. The system phase noise in this case is worse by $20 \times \log(n)$, where n is the multiplying factor. Microwave systems are particularly susceptible to reference oscillator phase noise, because the process of frequency multiplication increases the power in the sidebands by the square of the multiplication factor. A high precision, quartz-based, multi-output, triple-redundant space master oscillator is shown in Figure 1. Typically, these oscillators utilize a dual-oven construction, and a 5 MHz or 10 MHz, 5th overtone, SC-cut crystal resonator.

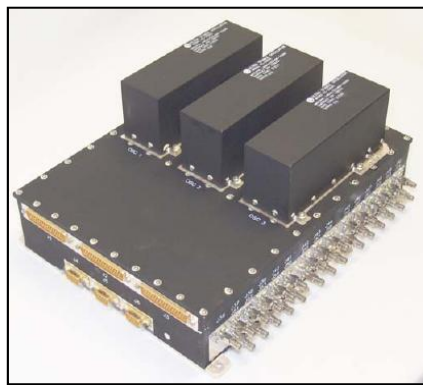


Figure 1. Triple-redundant space master oscillator.

For certain demanding applications, the master oscillator is required to maintain exceptionally low spur levels—better than -120 dBc in the frequency band of 10 Hz to 10 KHz and above. The expected spurious levels and degraded phase noise caused by the onboard micro vibrations, is illustrated in the following example:

- Assume a 10 MHz master quartz oscillator on a space vehicle operating in a typical on-orbit dynamic environment
- The random and sinusoidal vibration levels are specified in Table 1 below
- The static phase noise of the 10 MHz oscillator is specified in Table 2
- The g-sensitivity of the 10 MHz oscillator is $2 \times 10^{-9}/g$
- The required spurious levels are specified as -120 dBc from 0.5 Hz to 10 KHz.

Table 1. Random and sinusoidal vibration.

Random Vibration Frequency (Hz)	Power Spectral Density (g ² Hz)	Sinusoidal Vibration Frequency (Hz)	Vibration Acceleration (g)
1	0.00005	10	0.04
70	0.00009	40	0.06
130	0.00005	100	0.03
300	0.000004	300	0.006

Table 2. Oscillator static phase noise.

Off-set Frequency (Hz)	Static Phase Noise (dBc/Hz)
1	-116
10	-140
100	-150
1000	-155
10000	-160

The resulting theoretical performance is shown in Figure 2. The phase noise has been very much degraded by the random micro vibrations, and unacceptable spurious output levels have been generated due to the sinusoidal vibrations. Note that the sinusoidal vibration at 10 Hz has caused a spurious level of -88 dBc that is 32 dB greater than the specification requirement of -120 dBc. Similarly, at 10 Hz the phase noise is 40 dB worse than the quiescent level of -140 dBc/Hz.

The performance of the onboard master oscillator can be significantly improved when subject to the vibration levels shown in Tables I. One approach is to select crystals with better g-sensitivities. Assuming that a crystal with a g-sensitivity of $\sim 5 \times 10^{-10}/g$ is used, the phase noise and spurious levels in the above example will only improve by approximately 12 dB. Manufacturing 10 MHz, 5th overtone, SC-cut crystals with significantly better g-sensitivity than $5 \times 10^{-10}/g$ is very expensive and usually impractical.

A potentially better solution is to incorporate dynamic g-compensation. This approach is presently being tested by FEI on space-type oscillators, and preliminary data suggest that oscillators designed for space applications can achieve effective g-sensitivities of better than $5 \times 10^{-12}/g$.

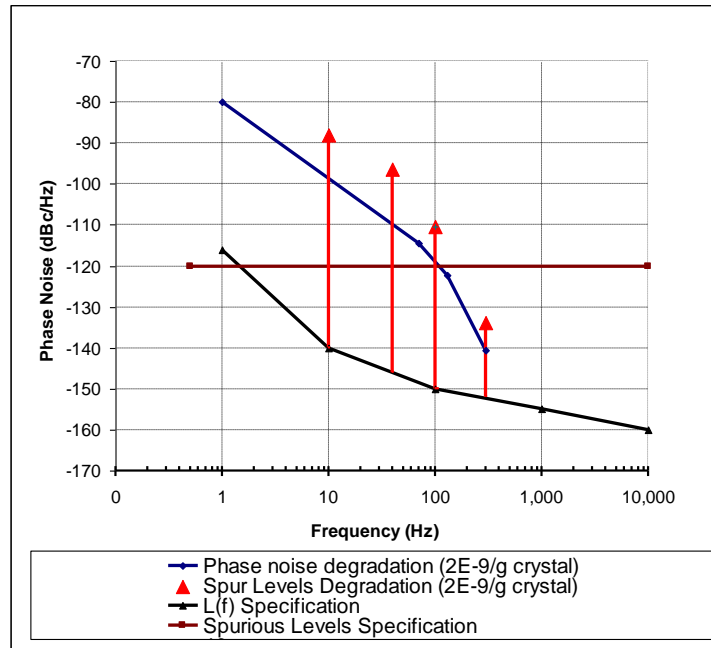


Figure 2. Single sideband phase noise and spurious levels degradation caused by typical satellite random and sinusoidal micro vibrations.

Questions and concepts to be considered:

- What really causes on board vibrations?
- Can onboard vibrations be measured (i.e. on Earth and/or in orbit)?
- What can be done to reduce on board vibrations?
- Is there an optimum location for the quartz oscillator on the spacecraft that will minimize the effects of vibration?

III. ONBOARD ELECTRIC DISCHARGES

Spacecraft charging and the possible damage to electronic equipment has been intensely studied and documented, resulting in various design guidance and guidelines intended to reduce mission disruptions (e.g., NASA-HDBK-4006, “Low Earth Orbit Spacecraft Charging Design Handbook” and NASA-HNDK-4402, “Avoiding Problems Caused By Spacecraft On Orbit Internal Charging EFFECTS”), but, nevertheless, anomalies in space continue to occur. The objective of this section is to present a concise and simplified overview of spacecraft charging and to postulate the effects that it may have on spaceborne quartz-based clocks.

R. D. Leach and M. B. Alexander [4] describe spacecraft charging as the process by which orbiting spacecraft accumulate electric charge from the surrounding natural space plasma and that the effects of spacecraft charging include the following:

- (1) Operational anomalies (i.e., telemetry glitches, logic upsets, component failures, spurious commands) caused by coupling of arc-discharge-induced transients into spacecraft electronics

- (2) Physical spacecraft surface damage (i.e., mirrored thermal control surfaces) as a result of arc-discharging
- (3) Degradation of spacecraft surface material thermal and electric properties due to increased surface contaminates.

Further examples and explanations of detrimental space environmental effects on avionics, electrical power, GN&C/pointing, material, optics, propulsion, structures, telemetry, tracking, communications, and mission operations is well documented by J. L. Herr and M. B. McCollum [5].

In general, spacecraft charging includes surface charging (external) and dielectric charging (internal), and both can have significant impact on a space mission when a discharge arc occurs. Surface or external charging is attributed to photoelectric current and low-energy plasma and internal or dielectric charging is caused by high-energy electrons that are able to penetrate the surface of the aircraft and deposit charges internally.

Wikipedia defines plasma as a partially ionized medium whereby a certain proportion of electrons are free rather than being bound to an atom or molecule. Hence, the ability of the positive and negative charges to move somewhat independently makes the plasma electrically conductive so that it responds strongly to electromagnetic fields. Energy in the natural space plasma charged particles causes them to move continuously; hence, moving charged particles create an electric current (i.e., moving electrons create a negative current, and moving positively charged ions create a positive current) [4]. The spacecraft charging is caused by charged particle motion in and transfer from the nearby plasma, and electrons with energy > 50 keV can penetrate spacecraft surface metallization to cause internal discharge [6,7].

For this paper, we shall only consider internal discharging, since it is the phenomena that causes internal arcing and can result in anomalies within a quartz-based clock. These high energy electrons build up on non-grounded parts such as floating metals and on other dielectric material and, as the charge continues to accumulate, the probability of an arc increases.

The effects of arc discharging are understood and various design practices are routinely implemented to reduce the probability of charge accumulations in the quartz clocks assemblies. Whenever practical, all metal is grounded; however, certain conductive parts such as toroids, coaxial-resonators, and various other elements are difficult to ground without disrupting circuit performance. Also, microstrip filters, hair-pin filters, and other microwave structures pose a significant challenge to engineers in their quest to eliminate any floating metal within the assembly. Furthermore, the advent of more compact circuitry reduces the proximity between potentially chargeable surfaces and other susceptible components, increasing the probability for an arcing incident to occur. The successful reduction of floating metals for the aforementioned examples are typically not shared with the space community, because they are considered trade secrets.

Questions and concepts that need to be considered:

- Effects of charging on quartz-crystal surface.
- Better guidelines for eliminating all floating metal without degrading performance.

IV. SOLAR FLARES AND SPACE RADIATION

“A solar flare occurs when magnetic energy that has built up in the solar atmosphere is suddenly released. Radiation is emitted across virtually the entire electromagnetic spectrum, from radio waves at the long wavelength end, through optical emission to x-rays and gamma rays at the short wavelength end. The amount of energy released is the equivalent of millions of 100-megaton hydrogen bombs exploding at the same time!” [8]. The solar flares phenomenon is well documented in the literature; hence, for the purpose of this paper we shall present a simplified explanation of the effects of solar flares and we shall again postulate the influence that it may have on spaceborne quartz-based clocks.

In general, a solar flare is the result of a large explosion in the sun’s atmosphere that causes electrons, protons, and ions to accelerate to near the speed of light, thus producing radiation in the entire electromagnetic spectrum. All low Earth-orbiting satellites and geostationary satellites operate within approximately 35,768 km or approximately 5.6 Earth radii or R_E ($1 R_E = 6371 \text{ Km}$) above the Earth and well within the Earth’s magnetic sphere that offers some protection from space radiation. The Earth’s magnetic sphere is referred to as the magnetosphere—the region above the ionosphere in which the magnetic field of the Earth has a dominant control over the motions of gas and fast charged particles [9]. The boundary of the magnetosphere is roughly bullet-shaped and, on the side facing the sun, the distance is about 10 to 12 R_E , while on the dark side it’s about 20 R_E , with the tail stretching well into 200 R_E and its end not well known.

However, solar flares do strongly influence the so-called Earth’s space weather in the Earth’s magnetosphere. This influence on the magnetosphere introduces radiation hazards to spacecraft. Recent data derived from the ESA-sponsored four spacecraft Cluster mission and two Double Star spacecraft demonstrated that the typical ion composition observed in the near-Earth environment was drastically modified by extreme solar events and that the magnetosphere became extremely compressed. GPS satellites orbit within the Earth’s protective magnetic bubble or magnetosphere, and during extreme solar events which are linked to solar explosions, the magnetosphere is compressed, and satellites are subjected to higher doses of radiation. Consequently, the electronic components, onboard memory, and cameras on board satellites can be greatly affected by extreme solar events [10]. In essence, during a solar flare a cascade of high energy particles known as a proton storm is released and, because this flux of very fast charged particles increases dramatically, it causes discharges in electronic components that are typically referred to as ‘single-event upsets,’ resulting in damage to circuit components and solid state memories and quartz resonators.

Satellites that travel past the Earth’s magnetosphere are at greater risk from the effects of solar flares and other galactic radiation.

In regard to the effects of radiation on quartz clocks, it can be stated that a small amount of space radiation is actually beneficial to the aging process and solar events are detrimental to the aging process. Both the beneficial and the detrimental effects of radiation are discussed below.

BENEFICIAL EFFECTS OF RADIATION ON QUARTZ CLOCKS

Quartz is sensitive to space radiation, and the performance of extensive tests on Earth have revealed some very interesting results that cannot only be used to predict performance in space, but can also be utilized to compensate the aging of the device. Figures 3 demonstrate the radiation effects on aging of a quartz oscillator in a controlled test environment [11].

- Radiation is applied to the OCXO Proto/Qual Unit on Day 0, and initially a short positive-transient aging response is observed, but over time (days 1-10) radiation is observed to be causing a negative trend in the aging process
- The average rate of space radiation has been calculated to be ≈ 6 rads/day, and the effect of 1 rad on a premium Q swept quartz crystal results in $\Delta f/f \approx -1 \times 10^{-12}$ with a total daily result of $\Delta f/f \approx -6 \times 10^{-12}$.

The plot in Figure 3 and the above equations demonstrate that radiation affects the aging process in a negative direction and, therefore, it can be stated that radiation is “beneficial” and can be advantageously utilized to actually compensate the aging trend of a monotonically positive-aging clock. In other words, the radiation effect offsets the positive aging of the crystal and acts as a compensatory mechanism.

A quality quartz clock that is robustly designed typically exhibits aging rates in the range of 10^{-11} /day after being tested and aged on Earth for a period of 90 to 180 days. This type of a clock can be expected to display on-orbit performance in the range of 10^{-12} /day.

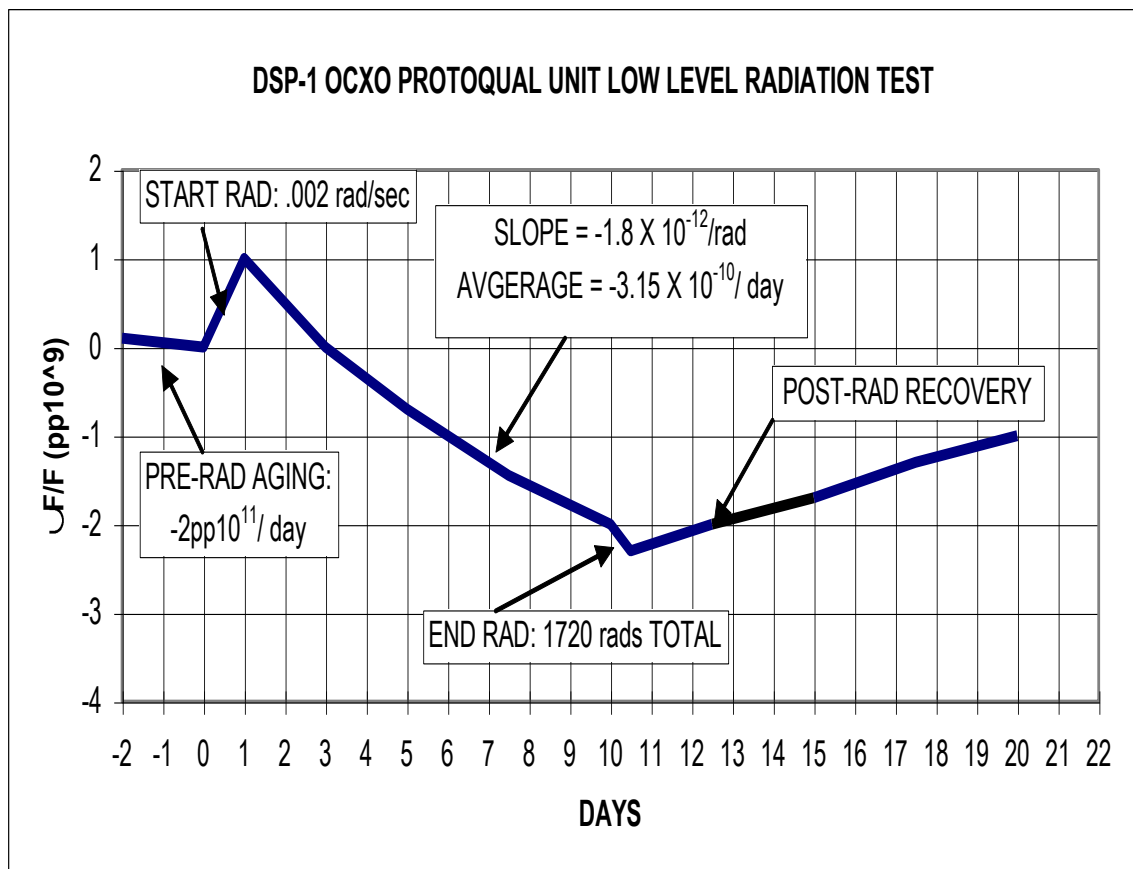


Figure 3. Radiation effect on a spaceborne OCXO proto/qual unit.

These expectations are supported with test results conducted on Earth, and with on-orbit-derived data from numerous space programs including Argos, Voyager, Fleet Sat Com, etc.

A. Argos clocks:

The following data was derived from 6 clocks:

Aging on Earth $\approx +2 \times 10^{-11}$ /day for typical unit
 $\approx +9 \times 10^{-11}$ /day for worst clock
Aging on-orbit $\approx 6 \times 10^{-12}$ /day after 5 years for typical unit
 $\approx 9 \times 10^{-12}$ /day after 5 years for worst unit.

B. Voyager clocks:

The following data was derived from clocks on two satellites, and an average aging rate was calculated as follows:

Aging on Earth $\approx +3 \times 10^{-11}$ /day
Aging on-orbit $\approx 3.4 \times 10^{-12}$ /day after 10 years.

Note: This clock is not in Earth's orbit.

C. Fleet Sat Com clocks:

Data derived from a fleet of 13 satellites:

Aging on Earth $\approx +2 \times 10^{-11}$ /day to $+4 \times 10^{-11}$ /day
Aging on-orbit $\approx 2 \times 10^{-12}$ /day to 4.4×10^{-12} /day after 15 years.

The on-orbit data was reported in the range of
 $+1.1$ to $+2.4 \times 10^{-8}$ /15 years.

Assuming a worst case linear function, the aging rate per day is calculated as follows:

$$(1.1 \times 10^{-8})/(365 \text{ days} \times 15 \text{ years}) \approx 2 \times 10^{-12}/\text{day}$$
$$(2.4 \times 10^{-8})/(365 \text{ days} \times 15 \text{ years}) \approx 4.4 \times 10^{-12}/\text{day}.$$

DETRIMENTAL EFFECTS OF RADIATION ON QUARTZ CLOCKS

As stated above, quartz is sensitive to radiation, and high energy particles resulting from solar flares can cause permanent frequency offsets. As an example, Figure 4 shows frequency aging for an 8-year period for oscillators on the MILSTAR program. The pronounced downward excursion in about month 72 (July 2000) in Figure 14 was due to solar flares, as reported in Presser and Camparo [12].

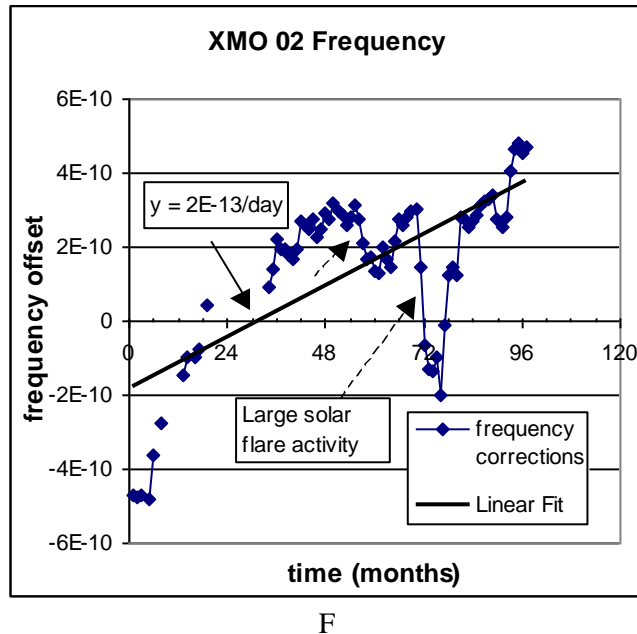


Figure 4. Long-term aging of a quartz oscillator on a MILSTAR satellite.

In contrast to quartz clocks, the effect of radiation on rubidium-based clocks is not a major concern. Aging data shown in Figure 5 suggest that radiation effects on rubidium clocks is at least down to the $\sim 10^{-14}$ level. This is further supported from data presented by Camparo, *et al.* on the effects of solar flares on clocks in space [13,14].

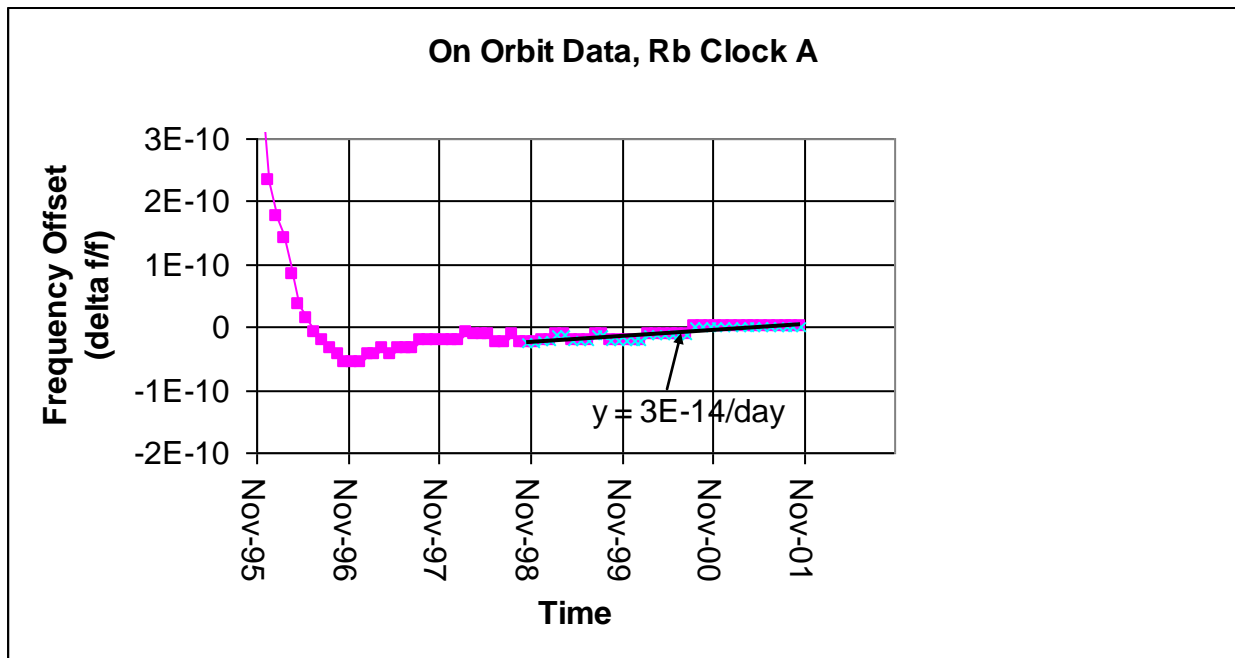


Figure 5. On-orbit data.

TEST RESULTS ON THE EFFECTS OF PROTON BOMBARDMENT OF QUARTZ RESONATORS

Proton radiation is not only a concern during solar storms. The region in space where the inner Van Allen radiation belt makes its closest approach to the Earth's surface (200-800 km, over the southern Atlantic Ocean) is known as the South Atlantic Anomaly (SAA), and is dominated by high-energy protons. Satellites in low Earth orbit (LEO) are exposed to this proton radiation whenever they pass through the SAA.

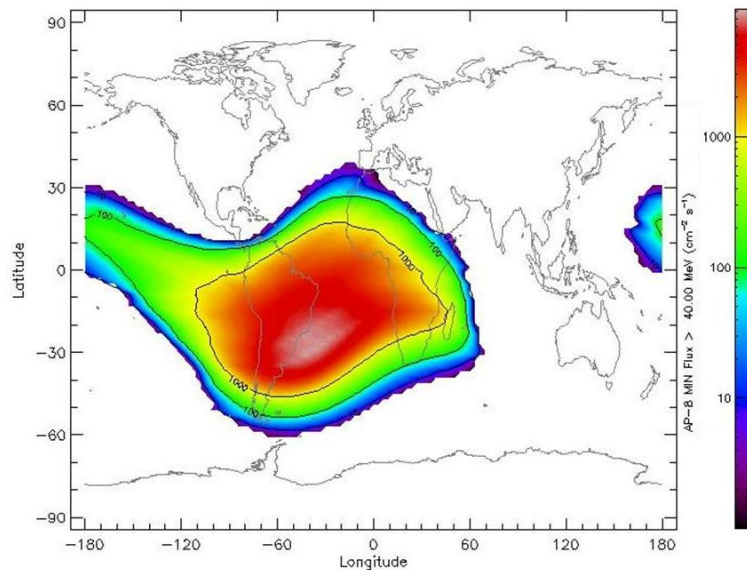


Figure 6. Contour plot of proton flux showing the region of intense proton radiation over the South Atlantic Ocean known as the South Atlantic Anomaly.

For quartz oscillators, onboard LEO satellites, the SAA is of particular concern [15]. The immediate effect of proton radiation on quartz oscillator frequency stability can vary over a wide range, depending on quartz crystal material purity, treatment, resonator frequency, overtone, and crystal cut.

Questions and concepts that need to be considered:

- Can radiation intensity and energy levels be more accurately determined?
- What causes the short-term frequency response of quartz resonators to proton radiation?
- Can resonators be designed that are less sensitive to radiation?
- Radiation effects on resonator Q.

V. SPACECRAFT TEMPERATURE EFFECTS

There are numerous factors that affect the stability of quartz oscillators; some have been discussed above, and in this section we shall present the effects of spacecraft temperature fluctuations. Thermal control systems are utilized on spacecrafts to stabilize internal temperatures. These systems are efficiently designed with minimum mass in order to lower launch expenses and to allow for additional equipment to be installed on the spacecraft. Those spacecraft orbiting the Earth experience extreme changes in temperature that can adversely effect internal components and systems. The spacecraft experiences

temperatures of over +150°C while on the sun's side and very cold temperatures of approximately -150°C when in the Earth's shadow. The thermal control systems perform adequately in maintaining a reasonable temperature stability internal to the spacecraft; however, these temperatures can still vary from -20°C to over +65°C and the rate of temperature change also varies from spacecraft to spacecraft. Quartz-based oscillator sensitivity to temperature changes has been well documented [16] and temperature-compensating techniques have been developed over the years to minimize the effects of temperature on oscillator performance. Excluding the quartz crystal, modern USO designs have practically eliminated as much as possible all temperature-varying components. The quartz crystal is the only major element that still requires temperature compensation. In general, the oscillator performance is greatly dependent on the type of crystal cut utilized.

As a historical perspective, in the mid 1950s, the AT-cut was invented by Arthur W. Warner at Bell Labs, and frequency stability levels of approximately $\pm 1 \times 10^{-8}$ were achieved over a large temperature range with AT-cut crystals. Double-rotated cuts were explored for many years, and in 1974 the stress-compensated cut was mathematically derived by Errol EerNisse. In addition to numerous other advantages over the AT-cut, the SC-cut proved to be a much better cut for applications in precision oven-controlled crystal oscillators (OCXO). For a more thorough explanation of AT and SC cuts, the reader is referred to the lectures of Dr. John Vig [16] and Errol EerNisse and John Kusters [17].

The latest techniques for temperature control in modern space oscillators include the utilization of SC-cut quartz crystals, dual ovens with precise circuitry to control the oven temperatures, all enclosed in a Dewar flask to reduce the effects of the spacecraft temperature environment. Figure 7 shows a well designed and constructed space oscillator that is able to maintain the temperature of the crystal to within 0.001°C in an environment with temperature excursions of over 100°C. The top structure represents a sealed Dewar flask containing the quartz crystal, dual ovens, and the oscillator circuitry. The bottom structure contains the voltage regulators and other pertinent circuitry. Both structures are housed in a mechanical enclosure. The final application of this type of oscillator is shown in Figure 8, where redundant oscillators (one oscillator is active and the other is in hot standby mode) are utilized for a certain space mission.

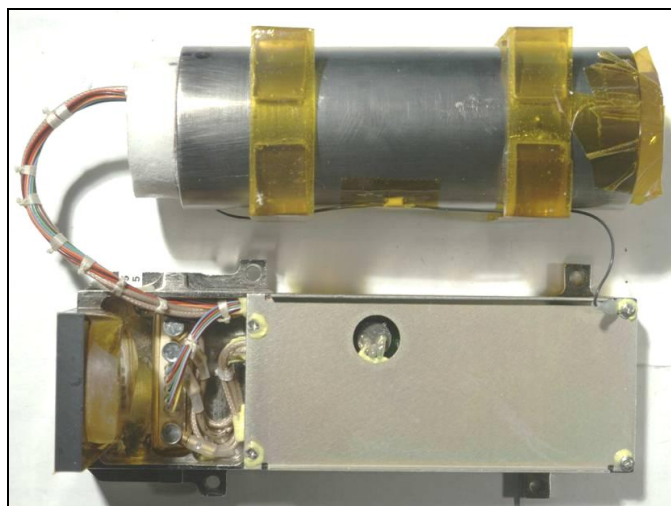


Figure 7. Ultra-stable temperature-compensated quartz-based space oscillator.

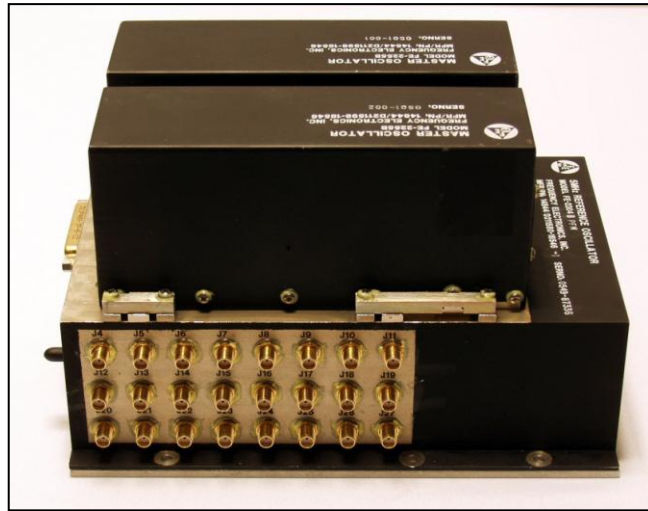


Figure 8. Redundant ultra-stable temperature-compensated quartz-based space oscillators.

Questions and concepts that need to be considered:

- Temperature interaction between the USO and other assemblies on the spacecraft
- How can we better protect against thermal effects?
- Are there sudden changes in temperature on spacecraft?
- Possibility to reliably measure the onboard daily temperature over the mission of the spacecraft.

VI. MAGNETIC FIELD EFFECTS

The sensitivity of quartz oscillators to magnetic fields is well known; however, there is minimal knowledge regarding the effects of magnetic fields on quartz clocks in space. Studies performed on the effects of magnetic fields on quartz resonators were conducted by Dr. Remi Brendel [19]. His experiments on quartz resonators demonstrate that magnetic fields interact with the ferromagnetic materials that are utilized to support the quartz disc, as shown in Figure 9. Quartz *per se* is not sensitive to magnetic fields, and Dr. Brendel postulates that the major cause for the resonator sensitivity to magnetic fields is due to the change in the elasticity—known as Young’s modulus—of the supports, and the effect is most pronounced when the magnetic field is directed normal to the plane of the resonator, as also shown in Figure 9. When the supports are subjected to a magnetic force, they extend under tension or buckle under compression, thus modifying the forces on the quartz disc and consequently affecting its resonant frequency. Furthermore, the sensitivity of the resonator is strongly dependent on the strength of the applied magnetic field.

In addition to the effects on quartz resonators, magnetic fields can adversely influence the performance of oscillator circuitry. Varying magnetic fields can induce Eddy currents that result in varying voltages that can affect varactors, AGC circuits, and power supplies [16].

Typical frequency change of an FEI well designed quartz oscillator is better than 10^{-11} per gauss.

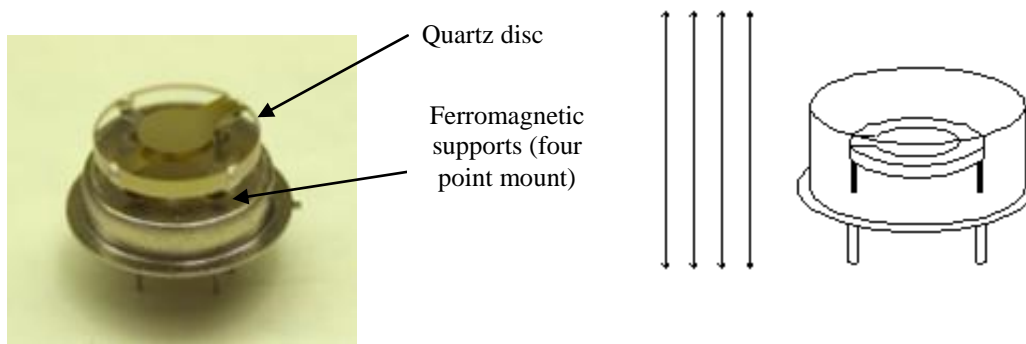


Figure 9. Resonator and magnetic field normal to the quartz disc.

In spacecraft environments, the quartz oscillator is subject to various known magnetic fields such as naturally occurring ones like the Earth's and other planetary magnetic fields, and manmade fields emanating from onboard magnetic stabilizing equipment, onboard traveling wave tubes, and other equipment. These fields will of course adversely affect the frequency stability of the onboard oscillator.

Questions and concepts that need to be considered:

- Improve resonator design to reduce magnetic sensitivity
- The utilization of components that are less sensitive to magnetic fields, especially inductors
- The possibility of obtaining reliable measured data of onboard magnetic fields.

VII. SPACE ARTIFICIAL (ORBITAL DEBRIS) AND NATURAL DEBRIS

As defined by the NASA Orbital Debris Program Office Web site [19], artificial debris (called orbital debris) is any manmade object in orbit about the Earth which no longer serves a useful purpose. Approximately 19,000 objects larger than 10 cm are known to exist. The estimated population of particles between 1 and 10 cm in diameter is approximately 500,000. The number of particles smaller than 1 cm probably exceeds tens of millions. Sputnik 1 launched 4 October 1957 became the first artificial space debris. A large concentration of orbital debris is found within 2,000 km of the Earth's surface. Within this volume, the amount of debris varies significantly with altitude. The greatest concentrations of debris are found near 800-850 km. NASA estimates that the average impact speed of orbital debris with another space object will be approximately 10 km/s. Consequently, collisions with even a small piece of debris will involve considerable energy. Natural space debris consists of meteorites, micrometeorites, asteroids, comets, etc. that are extremely large to very small dust grains.

NASA states that debris objects smaller than 0.1 cm generally do not penetrate spacecraft, 0.1 to 1 cm penetrate and damage spacecraft, and 1 cm debris objects and larger will cause catastrophic failure (loss of functionality of satellite due to impact)

The authors are not aware of any space debris having had a direct impact on quartz clocks in space; however, particle impacts may account for small frequency jumps in orbit. Consequently, the authors encourage that research be carried out on this subject.

VIII. CONCLUSION

Quartz-based spaceborne ultra-stable oscillators (USOs) have and will continue to be part of space missions. The spacecraft internal and external natural environment has a direct effect on the performance of the USO. The onboard environment is dynamic, with the presence of micro vibrations that cause the quartz oscillator to generate low-level spurious outputs and noise within commercial and military communications bands, resulting in degraded system performance. A concise and simplified overview of spacecraft charging has been presented and the possible effects that it may have on spaceborne quartz-based clocks has been discussed. The effects on quartz-based clocks of solar flares and the ensuing single-event offset have been presented. Spacecraft internal temperature variations have an effect on the USO and needs to be mitigated. The space orbital debris and natural debris impact on USO performance is unknown. The authors emphasize that future research be carried out on all subjects presented in this paper.

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